Geothermal Energy
a SpringerOpen Journal

RESEARCH Open Access

Hydrochemistry and geothermometry of an Albian aquifer from Oued Righ region in northeastern Algerian Sahara

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Abstract

Background: The area of Oued Righ is one of the important geothermal areas in northeastern Algerian Sahara. It is characterized by a hot arid climate with intense dryness and very high evaporation rates. The water requirements of the Oued Righ region are provided by groundwater resources contained in the two aquifers: the complex terminal and the deeper confined continental intercalaire aquifer.

Methods: Twenty-seven samples were taken in November 2010 and April 2012; Water samples were analyzed for major and minor dissolved chemical constituents.

Results: Samples collected from the CI aquifer are characterized by high temperatures varying from 40°C to 60°C and conductivities of 2110 to 3370 μS/cm. The total dissolved solids (TDS) of the thermal waters range from 1488 to 5480 mg/l. The waters are generally of sodium and magnesium sulfated and sodium chlorinated types. The results of mineral equilibrium modeling indicate that the thermal waters of Oued Righ are undersaturated with respect to evaporite minerals and oversaturated or nearly in equilibrium with respect to dolomite, calcite, and aragonite. This paper presents ternary diagrams of Na-K-$Mg^{1/2}$ and Cl-SO_4-HCO_3 and a calculation model, which allows location of geothermal water with the two diagrams, involving knowledge of their chemical composition.

Conclusions: Groundwater in the Albian aquifer of Oued Righ shows a change in its chemical properties between the two sampling periods, resulting from water-rock interactions and mixing processes.

Keywords: Continental intercalaire; Thermal waters; Oued Righ; Minerals

Background

The groundwater reservoir of the continental intercalaire (CI) is the deep reservoir of the septentrional Sahara. The continental intercalaire aquifer of North Africa is one of the largest confined aquifers in the world, comparable in scale to the great artesian basin of Australia and covers some 600,000 km^2 on only Algerian and Tunisian territories with a potential reservoir thickness of between 120 and 1000 m (Castany 1982).

The water chemistry is of Na-SO_4-Cl composition, and the total dissolved solids (TDS) of the thermal waters range from 1488 to 5480 mg/l. Its temperatures range from 40°C to 60°C. The current studies in the area are directed towards the geochemical evaluation of thermal waters in the Oued Righ field on the basis of chemical geothermometry and mineral equilibrium calculations.

Study area

The area is located in the northeastern Algerian Sahara. It is limited by large chotts and the piedmonts of Zab to the north, by the Mio-Pliocene and Turonien plateaus of the dorsal Mozabite and Daias plateaus to the west, by the sandy regs of the Ouarglie area to the south, and by the dune belt of the Grand Erg Oriental to the east. The study area is considered to be arid, the mean annual precipitation is less than 100 mm, and the mean annual temperature is around 22°C. The mean annual potential evapotranspiration is approximately 1165 mm.

Geology and hydrogeology

In the study area, there are two aquifer systems, separated by thick argillaceous and evaporitic series, base of the upper Cretaceous: the CI and complex terminal (CT) (Figure 1). The geology of the studied area has been investigated by several authors (Cornet 1964; Bishop 1975; Castany 1982). The CI aquifer is located within a complex succession of clastic

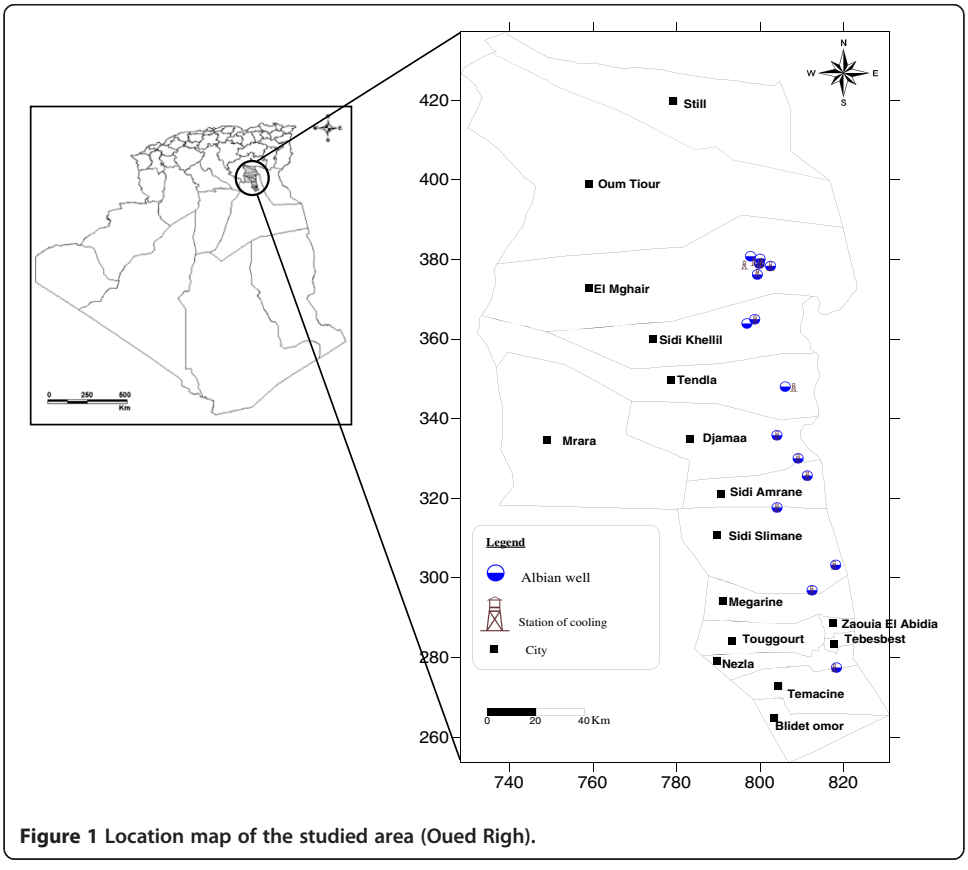

Figure 1 Location map of the studied area (Oued Righ).

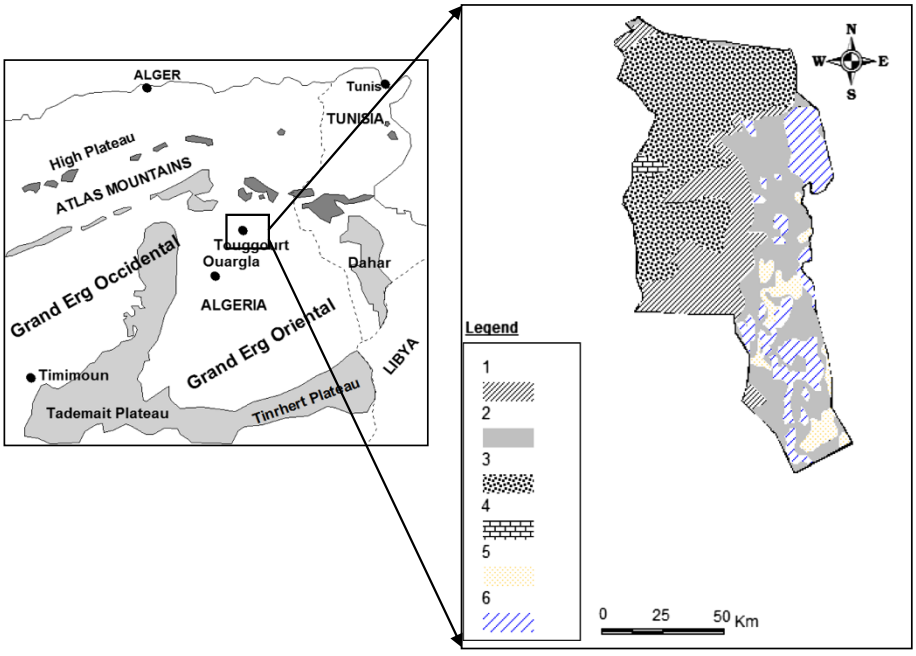

Figure 2 Geological map of the study area. This map is extracted from the geologic map of the Mesozoic basin of the Sahara Algero-Tunisian (Busson 1967). *1* Miocene or Pliocene (with locally continental nummulitic), *2* Quaternary, *3* Pliocene or former Quaternary, *4* upper middle Eocene, *5* dunes, *6* chotts.

sediments of Mesozoic age; the thickness and lithology of which show significant lateral variation (UNESCO 1972) (Figure 2).

The aquifer is, however, hydraulically continuous over the whole basin from north to south from the Saharan Atlas to the Tinrhet Plateau and further south to the Tassili Mountains of the Hoggar, and west to east from western Algeria to the Libyan border (Edmunds et al. 2003).

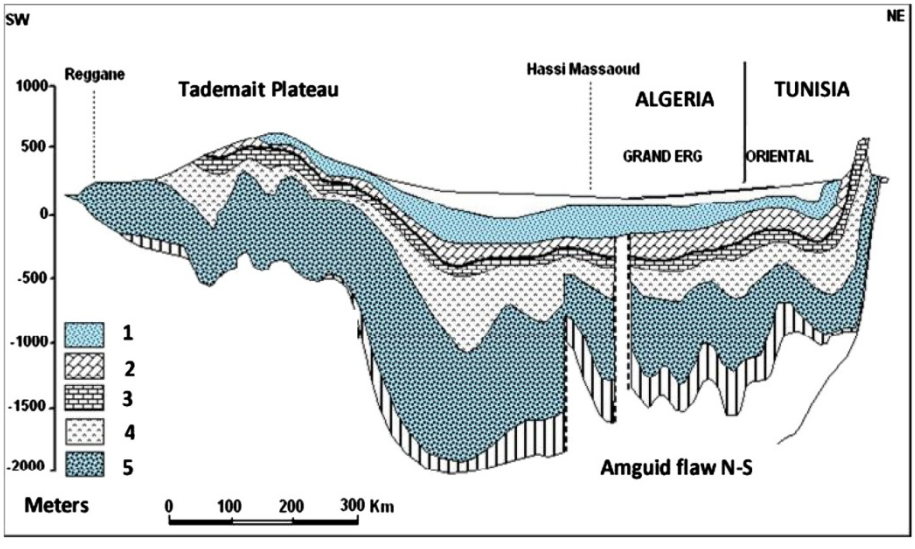

Figure 3 Synthetic hydrogeological section across the septentrional Sahara (UNESCO 1972). *1* Continental terminal aquifer, *2* Lower Senonian, *3* Turonian evaporates, *4* Cenomanian, *5* continental intercalaire aquifer.

Methods

Twenty-seven samples were taken in November 2010 and April 2012; the geographical location of the sampling site is shown in Figure 3. The physicochemical parameters (temperature, pH, and electric conductivity) were measured *in situ* using a WTW multi-parameter (Weilheim, Germany). Water samples were analyzed for major and minor dissolved chemical constituents. Ca, Mg, Cl, and HCO_3 were determined by the titration method. SO_4 was determined using spectrophotometric method. Na and K were analyzed using a flame photometer. Mineral saturation indices for a number of common minerals potentially present in the studied localities were calculated at measured discharge temperatures using PHREEQC 2.7 (US Geological Survey, Denver, Colorado) (Parkhurst and Appelo 1999) interfaced with Diagrams 5.8.

Results and discussion

Hydrogeochemical properties of thermal waters

Samples collected from the CI aquifer are characterized by high temperatures varying from 47.5°C to 60.4°C in November 2010 and 40.5°C to 61.3°C in April 2012 (Table 1). The conductivity values in the CI groundwater range from 2130 to 3300 μS/cm (November 2010) and 2110 to 3370 μS/cm (April 2012), having average TDS values of 1488 to 5480 mg/l (April 2012) and 1563 to 2047 mg/l (November 2010).

Dominant cations are mainly sodium and calcium and range, respectively, from 211.26 to 370.20 mg/l and from 108 to 208 mg/l (November 2010) (Table 2). The second period (April 2012) of the CI aquifer has sodium ranging from 117.5 to 298.75 mg/l and calcium varying between 132 and 216.8 mg/l (Table 3). Dominant anions are sulfate (266.18 to 4450.91 mg/l) and chloride (305.30 to 683.37 mg/l) in April 2012. The water samples for the period November 2012 are characterized by sulfate (410.10 to 714.54 mg/l) and chloride (312.40 to 695.80 mg/l). Variable water types may indicate different hydrogeochemical processes such

Table 1 Variation of temperature in Albian wells (April 2012 and November 2010)

April 2012		November 2010	
Well name	**Temperature (°C)**	**Well name**	**Temperature (°C)**
CI1ST22	53.2	CI1ST22	48.4
CI1ST10	50.3	CI1ST19	54.7
CI2SM4	49.5	CI1ST10	56.4
CI1SM5	49.2	CI1SD14	54.4
CI1SM3	55.5	CI3SD10	52
SD14	50	SD1	50.8
SD7	46.2	CI1SD5	53
SD1	49	CI1SD7	53.1
CI1SM1	41	CI2SM3	47.5
SD5	40.5	CI3SM3	58
SD10	52.7	CI1SM5	56.4
CI1SM4	59.9	CI1SM3	60.4
CI2SM3	49	CI1SM1	50
CI3SM3	61.3		

Table 2 Chemical data for the Albian aquifer from the study area (November 2010)

Sample ID	pH	C.E. (µS/cm)	Salinity (g/l)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	Cl (mg/l)	SO_4 (mg/l)	HCO_3 (mg/l)	CO_3 (mg/l)	TDS (mg/l)
Cl1ST22	8.78	2720	1.4	154.4	84.96	370.20	51.60	518.30	679.41	178.12	4.8	2042
Cl1ST19	8.7	2780	1.6	160	76.8	270.86	49.95	525.40	636.47	185.44	0	1905
Cl1ST10	8.66	3300	1.8	153.6	115.20	316.56	48.85	695.80	558.41	158.6	0	2047
Cl1SD14	8.33	2450	1.3	165.6	70.08	257.62	49.40	411.80	714.54	178.12	2.4	1850
Cl3SD10	8.16	2460	1.3	161.6	66.24	317.22	48.85	426.00	433.41	187.88	3.6	1645
SD1	7.52	2500	1.3	116	73.92	330.46	47.75	454.40	441.32	224.48	0	1688
Cl1SD5	8.81	2440	1.3	208	17.28	303.97	49.95	440.20	410.10	190.32	3.6	1624
Cl1SD7	8.91	2470	1.3	162.4	61.44	211.26	49.40	411.80	655.99	192.76	0	1745
Cl2SM3	8.97	2470	1.3	182.4	94.08	297.35	51.60	390.50	613.06	146.4	14.4	1790
Cl3SM3	9.1	2260	1.2	108	124.80	277.48	47.75	319.50	546.70	161.04	2.4	1588
Cl1SM5	8.7	2130	1.1	132	91.20	257.62	48.85	312.40	655.99	148.84	4.8	1652
Cl1SM3	8.94	2130	1.2	130.4	92.16	217.88	48.30	312.40	534.99	226.92	0	1563
Cl1SM1	9.33	2670	1.4	192	89.76	290.73	48.85	454.40	624.77	131.76	7.2	1840

C.E: electric conductivity

as mixing and water-rock interaction (El-Fiky 2008). A piper trilinear diagram (Figure 4) shows that all the thermal waters are characterized by the dominance of $Cl + SO_4$ over HCO_3 and Na + K over Ca + Mg for the period November 2010 and $SO_4 + Cl$ over HCO_3 and Ca + (Na + K) over Mg for the period April 2012. The sodium sulfated type is present in 53.85% of the samples for the period November 2010 and 7.14% for the period April 2012; some samples are rich in chloride and sodium, showing sodium chlorinated type which represents 46.15% (November 2010) and 7.14% (April 2012). The calcium sulfated type is present in 57.14% only for the period April 2012. Finally, the magnesium sulfated type

Table 3 Chemical data for the Albian aquifer from the study area (April 2012)

Sample ID	pH	C.E. (µS/cm)	Salinity (g/l)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	Cl (mg/l)	SO_4 (mg/l)	HCO_3 (mg/l)	CO_3 (mg/l)	TDS (mg/l)
Cl1ST22	7.3	2640	1.4	196.8	111.12	230	42.39	528.95	111.12	56.12	0	1488
Cl1ST10	7.76	3370	1.7	174.8	96.72	298.75	41.77	683.375	96.72	62.2	1.2	4101
Cl2SM4	8.17	2150	1.1	152.8	121.44	123.75	39.33	305.3	121.44	45.1	2.4	3813
Cl1SM5	8.24	2160	1.1	165.2	102.96	117.5	39.94	319.5	102.96	45.72	1.8	3491
Cl1SM3	7.42	2320	1.2	204.8	112.8	130	46.67	344.35	112.8	48.8	0	4945
SD14	8.05	2860	1.5	216.8	107.52	217.5	44.22	507.65	107.52	56.08	2.4	4762
SD7	8.14	2500	1.3	168	118.08	192.5	43.00	459.725	118.08	51.8	3	4573
SD1	7.23	2430	1.3	132	111.36	186.25	39.94	454.4	111.36	75.64	0	3480
Cl1SM1	8.26	2540	1.3	214.96	100.704	173.75	41.77	447.3	100.704	79.28	1.2	4267
SD5	8.27	2460	1.3	209.6	89.76	186.25	43.61	511.2	89.76	112.2	2.4	3447
SD10	7.36	2400	1.3	198.4	84.24	173.75	42.39	440.2	84.24	65.88	0	3752
Cl1SM4	7.13	2110	1.1	207.6	93.84	130	38.72	347.9	93.84	53.68	0	3509
Cl2SM3	8.34	2430	1.3	211.6	106.08	161.25	43.00	397.6	106.08	45.72	1.8	5480
Cl3SM3	7.55	2150	1.1	184.8	107.04	123.75	40.55	337.25	107.04	50.02	0	3651

C.E: electric conductivity

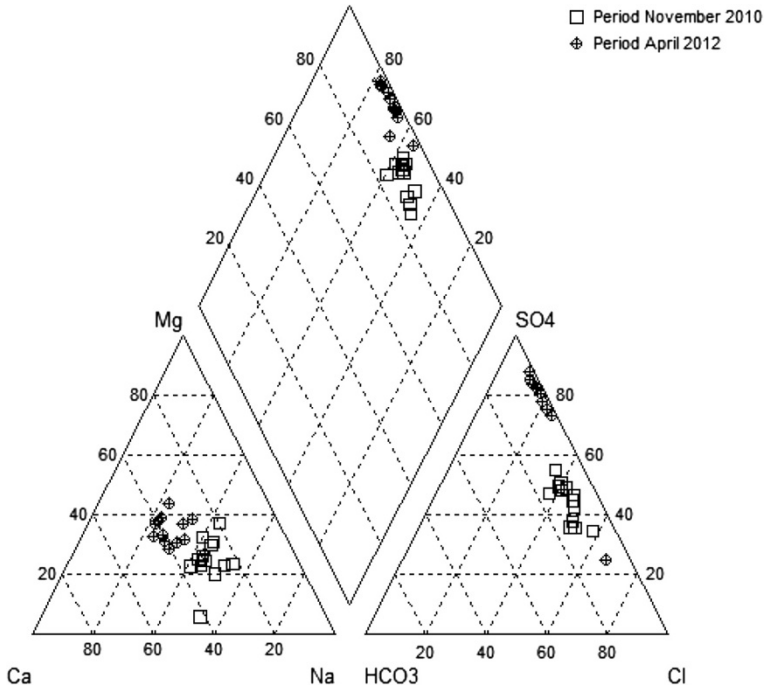

Figure 4 Distribution of the Cl thermal waters from the study area in Piper diagram. This is for the periods November 2010 and April 2012.

represents 28.57% for the period April 2012. This is due to the combination of mixing with cold groundwater and water-rock interaction processes in the thermal aquifers (Tarcan 2003).

Mineral saturation status

By using the saturation index approach, it is possible to predict reactive minerals in the subsurface from the groundwater chemical data without examining samples of the solid phases (Deutsch 1997).

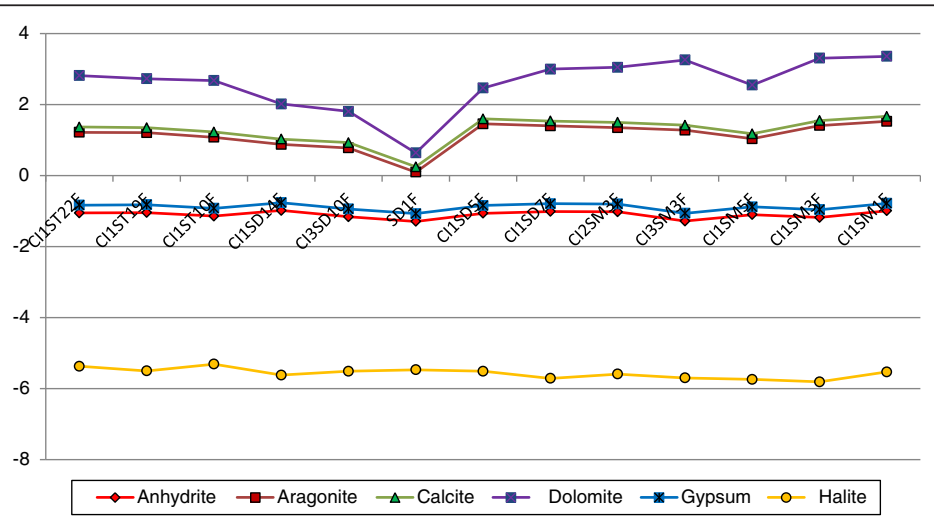

Figure 5 Saturation state of some minerals in Cl water from the Oued Righ area (November 2010).

In this study, the calculation of saturation indices of carbonate (calcite, aragonite, and dolomite) and evaporite (gypsum, anhydrite, and halite) minerals with respect to the calculated water composition was performed using the PHREEQC program (Parkhurst and Appelo 1999) which uses the WATEQ Debye-Hückel equation. Values of saturation index greater than, equal to, and less than zero represent oversaturation, equilibrium, and undersaturation, respectively. All thermal waters in the study area are undersaturated with respect to evaporite minerals (gypsum, anhydrite, and halite) for the period November 2010 and for the period April 2012, indicating that these minerals are undergoing dissolution (Figures 5 and 6), and explaining the high concentration of evaporite minerals in the reservoir. We may assume that the SI values falling within the range of ±0.5 units from 0 indicate the equilibrium state (Pulmmer et al. 1976). Most are oversaturated or nearly in equilibrium with respect to dolomite, calcite and aragonite for the period November 2010 and for the period April 2012, indicating that these carbonate minerals occur in the groundwater.

Water geochemistry

A geothermometric technique proposed by Giggenbach (1988) discriminates between immature waters and fully equilibrated waters originating in deep reservoirs. A total of 27 completed and analyzed groundwater samples from the CI were used in the Giggenbach diagram (Figure 7). The Na-K-$Mg^{1/2}$ ternary diagram (Giggenbach 1983) is used for evaluating equilibrium between the hot waters and rocks at depth and to estimate reservoir temperature. Figure 7 shows a Na-K-$Mg^{1/2}$ triangular diagram for thermal water samples from wells reaching the CI aquifer in Oued Righ data points plot adjacent to the $Mg^{1/2}$ corner, which is typical of 'immature waters' that do not attain equilibrium with their associated rocks or mixing with superficial waters.

All the samples collected in the CI aquifer are plotted in the Cl-SO_4-HCO_3 ternary diagram (Figure 8). It is shown that the waters of Oued Righ plot between the Cl and SO_4 fields of volcanic waters, but they never attain maturity.

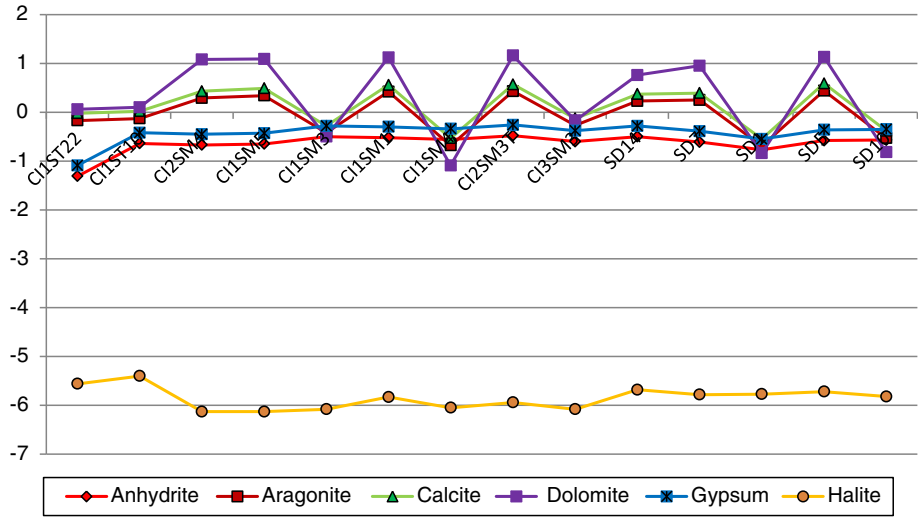

Figure 6 Saturation state of some minerals in CI water from the Oued Righ area (April 2012).

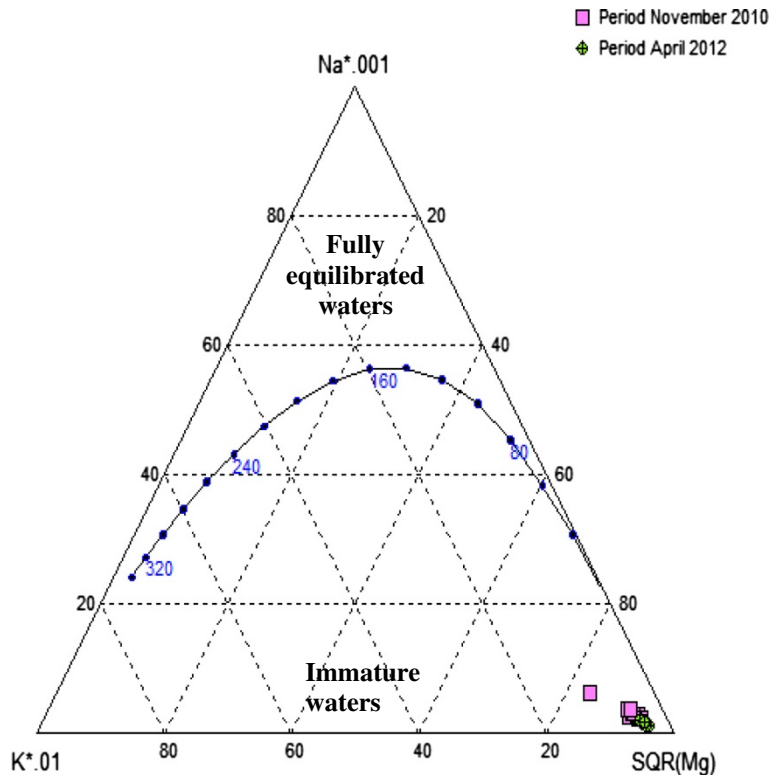

Figure 7 Distribution of the Cl thermal waters from the study area in the Giggenbach (1983) Na-K-$Mg^{1/2}$ triangular diagram.

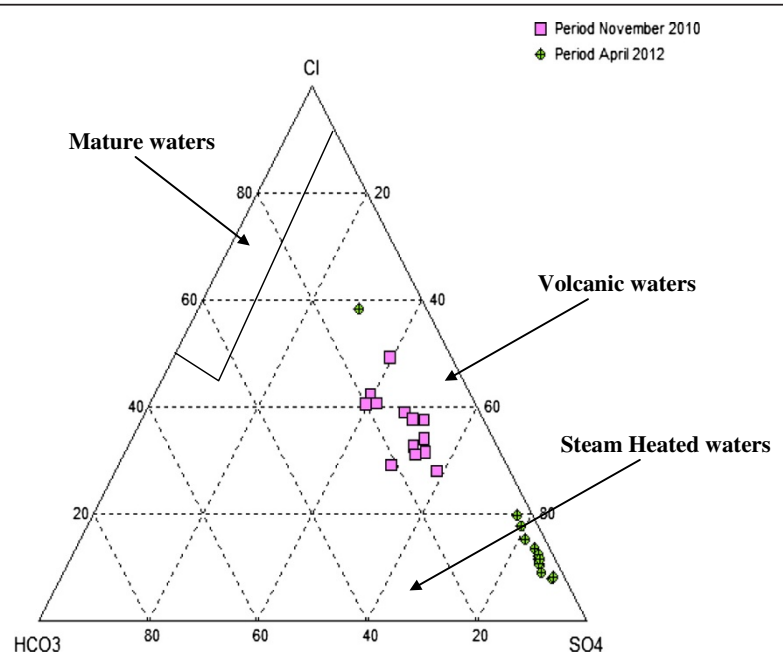

Figure 8 Distribution of the Cl thermal waters from the study area in the Cl-SO_4-HCO_3 triangular diagram.

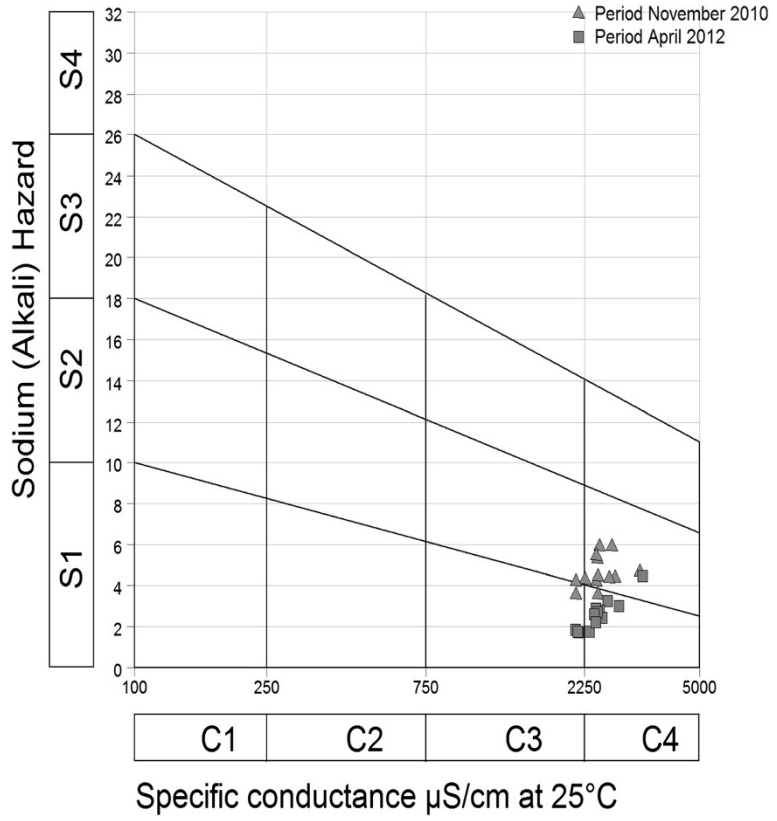

Figure 9 Salinity hazard of the Cl groundwaters of the study area (November 2010 and April 2012).

Water quality for irrigation

The suitability of groundwater for irrigation is dependent on the mineral constituents of water on the both the plant and soil (Maoui et al. 2010). In order to determine the suitability of groundwater for irrigation use, the Wilcox classification diagram (1955) in Figure 9 has been used. This graph is based on electrical conductivity (EC) and on sodium adsorption ratio (SAR). The SAR is of particular importance because a high Na content in irrigation water may increase soil hardness and reduce its permeability (Tijani 1994). High SAR can disperse soil aggregates, which in turn reduces the number of large pores in soil (Grattan 2002). Plotting of SAR on the Wilcox diagram (Figure 9) illustrates that most of the groundwater samples fall in the two fields (C3S1 and C4S1), indicating a very high salinity and low alkalinity hazard. This can be suitable for plants having good salt tolerance.

Conclusions

Groundwater in the Albian aquifer of Oued Righ shows a change in its chemical properties between the two sampling periods, resulting from water-rock interactions and mixing processes. The waters are generally of sodium and magnesium sulfated and sodium chlorinated types. The saturation indices of the study area show that evaporite minerals are undersaturated and carbonate minerals are oversaturated or nearly in equilibrium. The geothermal waters from the Oued Righ are immature waters, as indicated by the ternary diagram Na-k-$Mg^{1/2}$. Wilcox classification shows that most groundwater samples fall in to two fields (C3S1 and C4S1), indicating a very high salinity and low alkalinity hazard.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
This research is a part of the phd thesis. NK supervisor of the phd thesis. WC carried out the sample analysis and drafted the manuscript. Both authors read and approved the final manuscript.

Received: 30 July 2013 Accepted: 29 January 2014
Published online: 12 April 2014

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doi:10.1186/s40517-014-0003-3
Cite this article as: Chaib and Kherici: **Hydrochemistry and geothermometry of an Albian aquifer from Oued Righ region in northeastern Algerian Sahara.** *Geothermal Energy* 2014 **2**:3.